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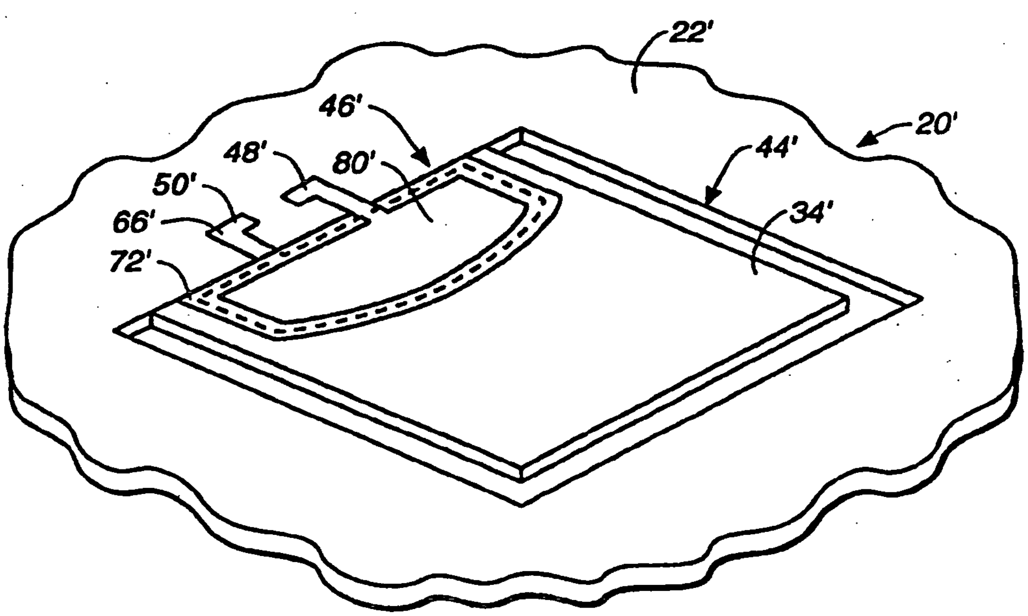

(57) Abstract

Micromachined cantilever pressure transducers (34), which work both as microphones and as microspeakers, are disclosed. These devices are made possible by novel methods for producing flat, thin film multilayer or polymeric cantilevers (34).

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CANTILEVER PRESSURE TRANSDUCER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Patent Application Serial No. 08/072,294, filed June 4, 1993, the disclosure of which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

The present invention relates generally to micromachined pressure transducers, and more particularly to a microphone or microspeaker comprising a cantilever structure.

Among the advantages of micromachining of pressure transducers are improved dimensional control, extreme miniaturization, the ability to integrate with on-chip circuitry, and potential low-cost as a result of batch processing.

Acoustic pressure transducers function as microphones or microspeakers. Microphones are pressure sensors that detect airborne sound pressures that are ten orders of magnitude lower than ambient pressure. Hence, a microphone needs an extremely compliant diaphragm to have an acceptable sensitivity. The diaphragm is the member that moves in response to changes in pressure.

The micromachined pressure sensors with piezoelectric readout initially had relatively thick diaphragms (on the order of tens of microns) bulk

micromachined from a substrate, such as single-crystal silicon. Control of the thickness and of the latent stress in such diaphragms was inadequate for use at very thin dimensions. When use of very thin, of the order of microns, diaphragms was attempted, the resulting diaphragm was warped.

A novel process for low-stress silicon nitride thin film deposition is disclosed in U.S. Patent No. 4,783,821, issued November 8, 1988. This process made possible the fabrication of thin-film diaphragm pressure transducers. The higher compliance of the thin-film diaphragm allowed production of more sensitive microphones. These and the earlier thick diaphragms are clamped on all four edges or all four corners, resulting in a tensioned diaphragm. The tensioning is necessary to control the shape of diaphragms whose residual stresses, together with the stresses of the transducers attached to the diaphragms, tend to warp them, even in the case of the newer low stress silicon nitride films. The tension, however, decreases the compliance of the diaphragm and, as a result, the sensitivity of the microphone.

Cantilever diaphragms are much more compliant than tensioned diaphragms. Use of a cantilever would increase the sensitivity of a microphone and the intensity of the output of a microspeaker. Maximizing the effective device area, minimizing acoustic leakage (reduction of the pressure difference on the two sides of the diaphragm due to air flow around it), and controllability of the device parameters, all require fabrication of substantially flat diaphragms. This has not heretofore been possible with thin-film, cantilever diaphragm and transducer structures. Attempts to fabricate such structures resulted not only in warped diaphragms, but in many cases the residual stresses led to breakage of the diaphragm during the cantilever patterning.

Accordingly, an object of the present invention is to provide a micromachined pressure transducer having a cantilever diaphragm.

Another object of the present invention is to provide a method for fabrication of a substantially flat cantilever diaphragm and transducer with high yield.

Additional objects and advantages of the invention will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by practice of the invention. The objects and advantages of the invention may be realized and obtained by means of the instrumentalities and combinations particularly pointed out in the claims.

SUMMARY OF THE INVENTION

The present invention is directed to a micromachined device having a cantilever structure covering the majority of an opening in a frame or substrate. When the cantilever structure is in equilibrium, its deflection out of the plane of the opening is less than about 100 μm.

The cantilever structure may include three adjacent sublayers, the middle one designated the second sublayer, and the other two designated first and third. The first and third sublayers have about the same average stress. The magnitude of the difference between the maximum and the minimum stress of the second layer, tensile and compressive stress being given opposite sign, is less than the magnitude of the average stress of the first sublayer.

The method of the present invention includes providing an article comprising a substantially planar first thin film having first and second exposed surfaces. Second and third films are grown on the first and second exposed surfaces of the first thin film. At least one slit is then etched through at least part of

the resulting thin film multilayer to define a multilayer thin film cantilever.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, schematically illustrate a preferred embodiment of the invention and, together with the general description given above and the detailed description of the preferred embodiment given below, serve to explain the principles of the invention.

Figure 1 is a perspective, partial cross-sectional view of a pressure transducer according to the present invention.

Figures 2A-2I are cross-sectional views, at several stages of fabrication of the transducer of Figure 1, along line 2-2 of Figure 1.

Figure 3A is a perspective view of a pressure transducer according to another embodiment of the present invention.

Figure 3B is a perspective view of a patterned silicon wafer used as part of a mold for casting the frame and cantilever of the pressure transducer of Figure 3A.

Figure 3C is a cross-sectional view of a mold for casting the frame and cantilever of the pressure transducer of Figure 3A.

Figure 4 is a graph of the surface profile of a cantilever structure according to the present invention.

Figure 5 is a graphical illustration of the residual stress as a function of thickness in a silicon nitride thin film.

Figure 6A is a cross-sectional view of a silicon nitride thin film membrane grown in one direction with only one surface exposed during the growth.

Figure 6B is a schematic diagram of the residual stress as a function of thickness of the membrane of Figure 6A and of the bending tendency of the membrane.

Figure 7A is a cross-sectional view of a silicon nitride thin film membrane grown according to the present invention.

Figure 7B is a schematic diagram of the residual stress as a function of thickness of the membrane of Figure 7A and of the bending tendency of the membrane.

Figure 8 is schematic diagram of the experimental set-up of the measurement of a microphone according to the present invention.

Figure 9 is a graph of the sensitivity of a microphone according to the present invention as a function of frequency.

Figures 10A and 10B are schematic diagrams of the experimental set-up of the measurement of a microspeaker according to the present invention.

Figures 11A and 11B are graphs of the response of a microphone according to the present invention as a function of frequency.

Figure 12 is a plan view of a pressure transducer according to the present invention shaped to increase the compliance of the cantilever diaphragm.

Figures 13 and 15 are plan views of pressure transducers according to the present invention comprising several cantilever structures.

Figures 14A-14C are cross-sectional views along line 14-14 of Figure 13 illustrating the possibility of coupling neighboring cantilevers.

Figure 16 is a schematic cross-sectional view of a sound intensity meter.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention will be described in terms of a number of preferred embodiments. The preferred embodiments are thin film cantilever pressure

transducers and methods for fabrication of such transducers. Such a structure 20 is shown in Figure 1.

Structure 20 comprises a substrate or frame 22 having a cavity 24. Substrate 22 may be 500-550 microns (μm) thick as indicated by dimension "t". Cavity 24 has openings 26 and 28 at surfaces 30 and 32 of substrate 22, respectively. Opening 26 may be a square having sides 2000 μm long. Covering a majority of opening 26 is a thin film cantilever structure 34 which may be 2-4 μm thick. Cantilever structure 34 has one captive edge 36 and three free edges 38, 40 and 42. A gap 44 surrounds the free edges. Gap 44 may be 10 μm wide. In order to minimize acoustic leakage, it is important to minimize the area of gap 44, such that cantilever structure 34 substantially covers opening 26. A transducer 46 such as a piezoelectric transducer overlaps cantilever structure 34 close to captive edge 36 but without overlapping substrate 22. Transducer 46 may comprise an insulated piezoelectric film sandwiched between two electrode films, one of which is exposed at the top surface of the transducer. For the sake of clarity, the piezoelectric film and two electrode films are not shown. Overlapping substrate 22 are contact 48 for the top transducer electrode and contact 50 for the bottom transducer electrode. Transducer 46 has one edge 53 parallel and very close to the captive edge 36 of cantilever structure 34, two other edges 52 and 54 parallel and close to edges 42 and 38 of the cantilever structure, and one edge 56 which preferably has the shape of a line of constant strain of cantilever structure 34 when subject to a pressure difference at its two surfaces.

The present invention may be practiced using transducers other than piezoelectric. For example, magnetostrictive, piezoresistive or, in the case of microspeakers, thermal transducers could be used.

The fabrication of transducer 20 will be described with reference to Figures 2A-2I. It may start using a prime grade, 4-inch (100) crystalline orientation silicon wafer as substrate 22. Silicon dioxide films 58a and 58b, approximately 0.2 μm thick, are thermally grown as shown in Figure 2A on surfaces 30 and 32 of substrate 22, respectively.

Low stress silicon nitride films 60a and 60b, approximately 0.5 μm thick, are then grown using low pressure chemical vapor deposition (LPCVD). The films are grown for two hours at a temperature of 835 °C, in a 300 millitorr (mTorr) ambient of 6:1 ratio dichlorosilane ($SiCl_2H_2$) and ammonia (NH_3).

Cavity 24 is fabricated next beginning with patterning of films 58b and 60b and substrate 22. First, the top surface of film 60a is covered with photoresist, which is hard baked without any exposure or developing. The back side of the substrate is next masked with photoresist and openings are patterned in the area to be etched to form cavity 24. Silicon nitride film 60b is plasma etched using a mixture of sulfur hexafluoride (SF_6) and helium. Thermal oxide 58b is wet etched in buffered hydrofluoric acid (HF). The photoresist is removed using an oxygen plasma and the silicon dioxide and nitride films are used as a mask during the silicon etching. Substrate 22 is wet etched anisotropically using a solution of Pyrocatecol or Catecol 320 g / Pyrazine 6 g / deionized water 320 milliliters (ml) / Ethylenediamine 1000 ml at 105 °C. This solution does not appreciably etch <111> planes of silicon, so that the resulting side walls of cavity 24 are <111> planes and there is very little undercut of films 58b and 60b. The silicon dioxide film 58a exposed by the etching of the substrate is next wet etched using hydrofluoric acid (HF). The resulting structure or article is shown in Figure 2B. The top opening of cavity 24 is closed by a thin film membrane 61. At this

stage in the processing, membrane 61 is made of silicon nitride film 60a, but in subsequent processing steps, as discussed below, additional films will be added to membrane 61, on both sides of film 60a.

Silicon nitride films 62a, 62b and silicon dioxide films 64a, 64b are deposited next using LPCVD. Films 62a, 62b are low stress silicon nitride, approximately 0.5 μm thick. These films are deposited for two hours at 835 °C, in a 300 millitorr (mTorr) ambient of 4:1 ratio $SiCl_2H_2$ and NH_3. Silicon nitride has been deposited on both sides of membrane 61. Films 64a, 64b are low-temperature oxide (LTO) silicon dioxide, approximately 0.2 μm thick. These films are deposited for 10 minutes (min) at 450 °C, in an ambient of 3:5 ratio silane (SiH_4) and oxygen. They are then annealed in nitrogen at 950 °C for 20 min. Silicon dioxide has been deposited on both sides of membrane 61. The resulting structure is shown in Figure 2C.

The lower electrode of transducer 46 is fabricated next, by depositing and patterning a polysilicon film. The polysilicon film is deposited by LPCVD and patterned by plasma etching as well known in the art. For example, an approximately 0.2 μm polysilicon film may be deposited in one hour at 610 °C, using 100:1 ratio of SiH_4 and phosphine (PH_3), followed by annealing in nitrogen at 950 °C for 20 min. Photoresist is then used to mask the area of the lower electrode of transducer 46 (Figure 1). The backside of the substrate is not masked, such that the polysilicon on the back side is etched completely. The polysilicon may be plasma etched in a mixture of carbon tetrachloride (CCl_4), helium and oxygen. After removal of the photoresist, the structure of Figure 2D is obtained. Transducer bottom electrode 66 overlaps membrane 61 close to its edge but without overlapping substrate 22. Contact lead 68 overlaps substrate 22.

Insulating layers 70a and 70b, shown in Figure 2E, are next deposited. These layers are approximately 0.2 μm thick LPCVD silicon dioxide deposited in one hour at 450 °C, using 60:100:10.3 $SiH_4/O_2/PH_3$. They are then annealed in nitrogen at 950 °C for 20 min. Again, both sides of membrane 61 are coated.

A piezoelectric zinc oxide (ZnO) film is then deposited and patterned. The film is grown by RF-magnetron sputtering onto a substrate heated to 200-300 °C, using a 1:1 mixture of argon and oxygen at a pressure of 10 mTorr, to a thickness of approximately 0.5 μm. No film is deposited on the back side. The film is patterned to form a pad 72 overlapping the polysilicon electrode 66, by photolithography without photoresist hard bake and wet etching using a 1:1:20 solution of acetic acid (CH_3COOH) / sulfuric acid (H_2SO_4) / H_2O. The photoresist is then removed using acetone, methanol and water for 30 minutes in each successively. The resulting structure is shown in Figure 2E.

A third layer of LPCVD silicon dioxide, approximately 0.3 μm thick is then deposited to encapsulate ZnO pad 72. As a result, films 74a and 74b are deposited on the front and back of membrane 61, respectively. The films are grown for 15 min at 450 °C, in an ambient of 60:100:0.4 $SiH_4/O_2/PH_3$.

Contact holes for contact to lead 68 are then etched through layers 74a and 70a. The holes are patterned with photolithography and the back side of the wafer is coated with photoresist to protect oxide films 64b, 70b and 74b. Holes 76 are then etched using buffered hydrofluoric acid. After photoresist removal, the structure of Figure 2F is obtained.

An aluminum film is next grown on the front side of the wafer for contact pad 78 and electrode 80. The film is sputtered to a thickness of approximately 0.8 μm, patterned by photolithography and wet etched as well known in the art, using a potassium ferrocyanide

($K_3Fe(CN)_6$) / potassium hydroxide (KOH) solution. A sacrificial backing aluminum film 82 is then sputtered on the back side to a thickness of approximately 0.5 μm. This film must be less than 1.5 μm thick to avoid breaking membrane 61 with its residual stress, but must be thick enough not to break when membrane 61 is etched as described below. The resulting structure is shown in Figure 2G.

The shape of cantilever 44 is next defined by etching gap 44 (Figure 1). After photolithography on the front side, membrane 61 is etched down to the sacrificial backing aluminum layer 82. Wet etching is used for the silicon dioxide layers, and plasma etching for the polysilicon and silicon nitride layers as described above, resulting in the structure of Figure 2H. Aluminum layer 82 increases the yield by preventing breakage of membrane 61 during this etching step.

Finally, sacrificial backing layer 82 is removed by wet etching after masking the front side to protect electrode 80 and contact pad 78. After removing the photoresist, the structure of Figures 1 and 2I is obtained.

The wafer may then be diced with a diamond saw, and individual pressure transducers glued and wire-bonded to ceramic packages which have a 3 millimeter (mm)-diameter ventilation hole formed by a diamond drill. The ventilation hole may be left open during testing or sealed to form a 15 mm^3 back-cavity volume. The ventilation hole may be sealed by gluing a suitable backing over the hole on the underside of the ceramic package.

Figure 3A shows another pressure transducer 20' according to the present invention. This transducer is a polymeric cantilever structure with a thickness of a few to tens of microns. Device 20' comprises a frame 22', a cantilever structure 34' and a transducer 46'. Cantilever structure 34' is separated from frame 22' by

a gap 44' over part of the perimeter of structure 34', and is attached to frame 22' over the rest of its perimeter. Overlapping cantilever structure 34' near the portion of its perimeter attached to frame 22' is transducer 46'. Transducer 46' may comprise a piezoelectric layer 72' sandwiched between a lower electrode 66' and an upper electrode 80', having leads 50' and 48', respectively.

With a suitable choice of materials, pressure transducer 20' may be made thin and flexible. Electrodes 66' and 80' and leads 50' and 48' may be thin metal films, and frame 22', cantilever structure 34' and piezoelectric layer 72' may be formed of polymeric materials. For example, frame 22' and cantilever structure 34' may be formed of a structure polymer such as polycarbonate, polystyrene or polyimide. The piezoelectric layer may be PvDF (polyvinylidene difluoride) and TrFE (trifluoroethylene). Such a polymeric pressure transducer may be made integral with other polymer-based objects such as credit cards and smart cards.

Frame 22' and cantilever structure 34' may be cast at the same time using a reusable micromachined mold that may be advantageously made by etching a silicon wafer 86 (Figure 3B) to form features 88 raised above surface 87 from a few to tens of microns. Features 88 have the shape of the gap 44' to be formed in the resulting polymer structure. Before casting, the surface 87 of mold wafer 86 may be coated with a mold release agent such as a silating agent with fluorocarbon backbone, assuming the mold is made of silicon. Mold wafer 86 may then be coated with a structure polymer precursor, after which a second, flat wafer 90 is put on top of wafer 86. Figure 3C is a cross-sectional view of the resulting assembly. This arrangement limits the thickness of the structural polymer coating so that it does not overflow features 88.

After polymerization which may be accomplished using a variety of well-known methods, wafer 90 may be removed but frame and cantilever structure 22' and 34' should be left in place on wafer 86 for ease of handling during subsequent processing steps.

Transducer 46' is fabricated next. Lower electrode 66' may be evaporated through a shadow mask. The piezo polymer layer 72' may then be applied by spinning on while an aperture mask is in place over the underlying structure. Upper electrode 80' is then applied, also by evaporation through a shadow mask. Piezoelectric layer 72' may then be poled by applying a voltage between electrodes 66' and 80' during which time the piezoelectric layer is heated and then allowed to return to room temperature.

The advantages of the process described above with reference to Figures 2A-2I will be discussed next. It is desired that the resulting cantilever structures 34 (Figure 1) have out-of-plane deflections less than 100 μm at equilibrium (i.e., when not acted upon by external forces), preferably less than 50 μm and more preferably significantly less than 50 μm. Figure 4 shows the profile of the highest-deflection section of an actually fabricated cantilever structure, such as structure 34 of Figure 1, as measured by a profilometer. The vertical axis indicates deflection in microns, and the horizontal axis indicates the position along the cantilever in microns, the captive edge of the cantilever being at a position "x" of approximately 400 μm from the origin. As can be seen, the out-of-plane deflection of the transducer is less than 20 μm. By means of non-contact optical measurements, it has been verified that the profile of Figure 4 is accurate to within experimental error of 3 μm. Across a given wafer, the majority of the transducers of the present invention have out-of-plane deflections below 35 μm.

Cantilever structures fabricated with the entire silicon nitride deposition as a single layer before the substrate etching were significantly curled upward or downward. As discussed above, this is undesirable because it decreases the effective device area upon which the sound wave impinges in the case of a microphone, or which launches the sound wave in the case of a microspeaker. Additional reasons why a curled cantilever structures are undesirable are an increase in acoustic leakage and possible lack of controllability of the device characteristics.

The downward curl is due to the high residual compressive stress of the ZnO layer of the piezoelectric transducer. It was found that the curl is considerably reduced by patterning the ZnO, such as layer 72 of transducer 46 (Figure 2I), so that it does not overlap the silicon frame.

The upward curl of the single silicon nitride layer cantilever structures arises because of the gradient of residual stress of the silicon nitride, which is illustrated in Figure 5 for a typical film deposited as a single layer onto a bulk substrate, such as film 91 of Figure 6A. The stress profile of Figure 5 has been obtained by successively removing thin layers of such a film and measuring wafer curvature. In Figure 5, the vertical axis indicates position along the thickness of a film and the horizontal axis indicates residual stress in megaPascal (MPa), positive for tensile stress and negative for compressive stress. The stress distribution in the silicon nitride seems to be related to annealing during the deposition at 835 °C. The earlier a layer is deposited, the longer this layer is annealed. The gradient in the residual stress of a film grown onto a surface of a bulk substrate in only one direction, such as silicon nitride film 91 in Figure 6A, generates a moment that causes the upward curl, indicated by arrow A in Figure 6B where the vertical

axis indicates position along the thickness of film 91 and the horizontal axis indicates residual stress. Cavity 93 of Figure 6A was etched, after the growth of film 91, in substrate 95.

Figure 7A shows the solution used in the process flow of Figures 2A-2I in order to produce a cantilever with a symmetric stress distribution in the silicon nitride. It should be noted that the stress distribution in the finished diaphragm, with outer silicon dioxide layers, will also be symmetric for the reasons given below. The initial approximately 0.5-μm-thick silicon nitride layer 92, corresponding to layer 6a in Figure 2I, is deposited with a 6:1 reactant gas ratio to form the diaphragm prior to bulk micromachining. The low (50 MPa) residual tensile stress of the thin, initial diaphragm makes it more resistant to rupture.

After bulk micromachining, the second approximately 0.5-μm-thick low-stress silicon nitride 94, corresponding to layers 62a and 62b in Figure 2I, is deposited with a 4:1 reactant gas ratio. The larger tensile stress (250 MPa) of the second layer is used to maintain diaphragm flatness during subsequent processing steps. Since the second silicon nitride deposition occurs on both sides of the original diaphragm, the stress gradients become symmetric as shown in Figure 7B. The first silicon nitride layer is also annealed during the second layer deposition and its stress distribution becomes negligible. The result is a relatively flat cantilever. This technique of producing a flat cantilever despite the stress gradient in the component films may have applications to other micromachined structures.

The microphone frequency response of the structure of Figure 1 has been measured using the arrangement of Figure 8. The measurement was made in an electrically shielded anechoic chamber 96 containing a

calibrated reference microphone 100. The test (cantilever diaphragm) microphone 98 of the present invention (whose structure 20 is shown in Figure 1), and reference microphone 100, respectively, were placed at the same distance from the source of acoustic signals, which was at the end of a 6.5 mm diameter tube 102 that leads into the chamber from an external conventional loudspeaker 104 driven by spectrum analyzer 108. The output signals of test microphone 98 and reference microphone 100 were applied, using lead pairs 99 and 97, respectively, to the input of a high input impedance amplifier 106 connected to spectrum analyzer 108.

Figure 9 shows the typical measured microphone sensitivity (curve A) when tested without the above-described ceramic package hole backing. The vertical axis indicates sensitivity in mV/μbar (millivolts per microbar, 1 bar = 10^5 Pa) and the horizontal axis indicates the frequency. The microphone sensitivity is fairly constant at 2 mV/μbar in the low frequency range and rises to 20 mV/μbar at the lowest resonant frequency of 890 Hz. The 2 mV/μbar is the highest reported for a microphone with a micromachined diaphragm. The low-frequency sensitivity and the resonant frequencies are in good agreement with a simulation result given by curve B. Independent testing showed that backing with a 15 mm^3 cavity reduces the low-frequency sensitivity by about 8 decibels (dB), to around 0.8 mV/μbar. The simulation result was obtained using a combination of finite-element simulations and analytical modeling.

The microspeaker frequency response of the structure of Figure 1 has been measured using the arrangement of Figures 10A and 10B. The acoustic output of the cantilever device 110 of the present invention (whose structure 20 is shown in Figure 1), driven by spectrum analyzer 108 through leads 109, was measured using a 2 cm^3 coupler 112 with a calibrated microphone 114 connected to spectrum analyzer 108 with leads 107.

Figure 11A shows the microspeaker output in the 100 Hz to 10 kHz frequency range with 4V (zero-peak) input drive. Figure 11B shows the sound pressure level produced by the microspeaker in the 1 kHz to 50 kHz frequency range. In Figures 11A and 11B, the vertical axis is sound pressure level in dB SPL (decibels sound pressure level) and the horizontal axis is frequency. The resonant frequencies coincide with those of the microphone response at 890 Hz and 4.8 kHz, as expected. The highest output pressure corresponds to approximately 100 dB SPL.

As shown in Figure 12, which is a plan view of a cantilever pressure transducer 111 of the present invention, the compliance of the diaphragm may be further increased by reducing the length of the diaphragm perimeter where the diaphragm is attached to the frame 120 and providing a narrower portion 116 carrying transducer 46 near the captive edge of diaphragm 34, where most of the diaphragm bending takes place. Transducer 111 may be fabricated using either the method of Figures 2A-2I or of Figures 3A-3C.

Figures 13 and 15 are plan views of cantilever pressure transducers 119 and 121, according to the present invention, respectively. Transducers 119 and 121 may be fabricated using either the method of Figures 2A-2I or of Figures 3A-3C. Transducers 119 and 121 have a plurality of cantilever structures 117 sharing an opening 118 in a frame 120. Transducer 119 has five cantilever structures 117, and transducer 121 has eight cantilever structures 117. In Figure 15, the opening is substantially circular and the cantilever structures are positioned substantially radially over the opening. As shown in Figure 14A, the cantilever structures may be free and separated by gaps 124, or, as shown in Figures 14B and 14C, the cantilever structures may be coupled by thinner (120, Figure 14B) or corrugated (122, Figure 14C) diaphragms. These options provide additional

flexibility in the design of pressure transducers allowing control over the details of their frequency response.

Figure 16 shows how two cantilever pressure transducers 126 and 128 can be stacked to form a sound intensity meter 132. As is well known, the upper limit of the frequency range over which the intensity meter is functional is increased by locating the pressure transducers closer to each other. Pressure transducers 126 and 128 may be located at a short distance relative to each other using spacers 130.

In summary, micromachined cantilever pressure transducers, such as microphones and microspeakers, and methods for their fabrication have been described. By controlling the distribution of residual stress, 2000 μm long cantilevers were fabricated whose maximum out-of-plane deflections were typically no more than 35 μm. The microspeaker output is proportional to the input drive, and rises to approximately 100 dB SPL at 4.8 kHz and 6V (zero-peak) drive. The microphone sensitivity is fairly constant at 2 mV/μbar in the low frequency range, and is 20 mV/μbar at the lowest resonant frequency of 890 Hz. The high microphone sensitivity and the high microspeaker output are due to the high compliance of the cantilever diaphragm.

The present invention has been described in terms of a preferred embodiment. The invention, however, is not limited to the embodiment depicted and described. Rather, the scope of the invention is defined by the appended claims.

WHAT IS CLAIMED IS:

1. A micromechanical device comprising:

a frame having an opening; and

at least one cantilever structure attached to said frame over a portion of a perimeter of said opening and covering a majority of said opening; and

wherein when said cantilever structure is in equilibrium, its deflection out of the plane of said opening is less than about 100 μm.

2. The device of Claim 1 wherein said cantilever structure includes silicon nitride.

3. The device of Claim 1 wherein said frame and said cantilever structure include a polymeric material.

4. The device of Claim 1 further including a second device according to Claim 1 at a predetermined position to form a sound intensity meter.

5. The device of Claim 1 further including a transducer, said transducer overlapping said cantilever structure and not overlapping said frame.

6. The device of Claim 5 wherein said transducer is from the group consisting of piezoelectric, piezoresistive, capacitive, magnetostrictive and thermal transducers.

7. The device of Claim 5 wherein said transducer includes a zinc oxide thin film.

8. The device of Claim 1 wherein, when said cantilever structure is in equilibrium, its deflection out of the plane of said opening is less than about 50 μm.

9. The device of Claim 8 wherein said cantilever structure includes silicon nitride.

10. The device of Claim 8 wherein said frame and said cantilever structure include a polymeric material.

11. The device of Claim 8 further including a transducer, said transducer overlapping said cantilever structure and not overlapping said frame.

12. The device of Claim 11 wherein said transducer is from the group consisting of piezoelectric, piezoresistive, capacitive, magnetostrictive and thermal transducers.

13. The device of Claim 11 wherein said transducer includes a zinc oxide thin film.

14. A micromechanical device comprising:

a substrate having a first and second surfaces and a cavity with an opening at said first surface; and

at least one multilayer cantilever structure attached to said first surface of said substrate over a portion of a perimeter of said opening and covering a majority of said opening; and

wherein said cantilever structure includes three adjacent sublayers designated first, second and third such that said second sublayer is adjacent to said first and third sublayers; said first and third sublayers having about the same average stress; said second sublayer having a maximum stress and a minimum stress, compressive and tensile stresses considered to have opposite sign; and the magnitude of the difference between said maximum stress and said minimum stress being less than the magnitude of the average stress of said first sublayer.

15. The device of Claim 14 wherein said first, second and third sublayers include silicon nitride.

16. The device of Claim 14 further including a transducer, said transducer overlapping said cantilever structure and not overlapping said substrate.

17. The device of Claim 16 wherein said transducer is from the group consisting of piezoelectric, piezoresistive, capacitive, magnetostrictive and thermal transducers.

18. The device of Claim 16 wherein said transducer includes a zinc oxide thin film.

19. The device of Claim 14 wherein said first and third sublayers have opposite stress gradients.

20. The device of Claim 19 wherein said first, second and third sublayers include silicon nitride.

21. The device of Claim 19 further including a transducer, said transducer overlapping said cantilever structure and not overlapping said substrate.

22. The device of Claim 21 wherein said transducer is from the group consisting of piezoelectric, piezoresistive, capacitive, magnetostrictive and thermal transducers.

23. The device of Claim 21 wherein said transducer includes a zinc oxide thin film.

24. The device of Claim 14 wherein an average stress of said second sublayer is less than the average stress of said first layer.

25. The device of Claim 24 wherein said first, second and third sublayers include silicon nitride.

26. A method for fabrication of a thin film cantilever structure, comprising:

providing an article comprising a substantially planar first thin film, said thin film having first and second exposed surfaces;

growing second and third thin films on said first and second surfaces, respectively, to form a thin film multilayer; and

etching at least one slit through at least part of the thin film multilayer to define at least one multilayer thin film cantilever.

27. The method of Claim 26 further including:

growing a sacrificial backing layer before etching said slit; and

etching said sacrificial backing layer after etching said slit; and wherein

said sacrificial backing layer is not etched when said slit is etched.

28. The method of Claim 26 wherein said second and third films are grown at the same time.

29. The method of Claim 28 wherein said second and third films are grown using chemical vapor deposition.

30. The method of Claim 29 wherein said second and third films include silicon nitride.

31. The method of Claim 26 wherein said first film includes silicon nitride grown on a silicon dioxide-coated substrate by chemical vapor deposition in

an atmosphere with ratio of silicon atomic content to nitrogen atomic content of about 6:1.

32. The method of Claim 26 further including a step of growing fourth and fifth thin films on said second and third thin films, respectively before the etching of said slit.

33. The method of Claim 32 further including

growing a sacrificial backing layer before etching said slit; and

etching said sacrificial backing layer after etching said slit; and wherein

said sacrificial backing layer is not etched when said slit is etched.

34. The method of Claim 32 wherein said fourth and fifth films are grown at the same time.

35. The method of Claim 34 wherein said fourth and fifth films are grown using chemical vapor deposition.

36. The method of Claim 35 wherein said fourth and fifth films include silicon dioxide.

37. A method for fabrication of a polymeric cantilever structure, comprising:

providing a first mold element having features raised above a first flat surface;

coating said first surface with a polymer precursor;

placing a second mold element with a second flat surface parallel to the first surface and in contact with the raised features; and

polymerizing said polymer precursor.

38. A micromechanical device comprising:

a frame having an opening; and

a plurality of cantilever structures, said cantilever structures being attached to said frame over portions of a perimeter of said opening and covering a majority of said opening; and

wherein when said cantilever structures are in equilibrium, their deflection out of the plane of said opening is less than about 100 μm.

39. The device of Claim 38 wherein said opening is substantially circular and said cantilever structures are positioned substantially radially above said opening.

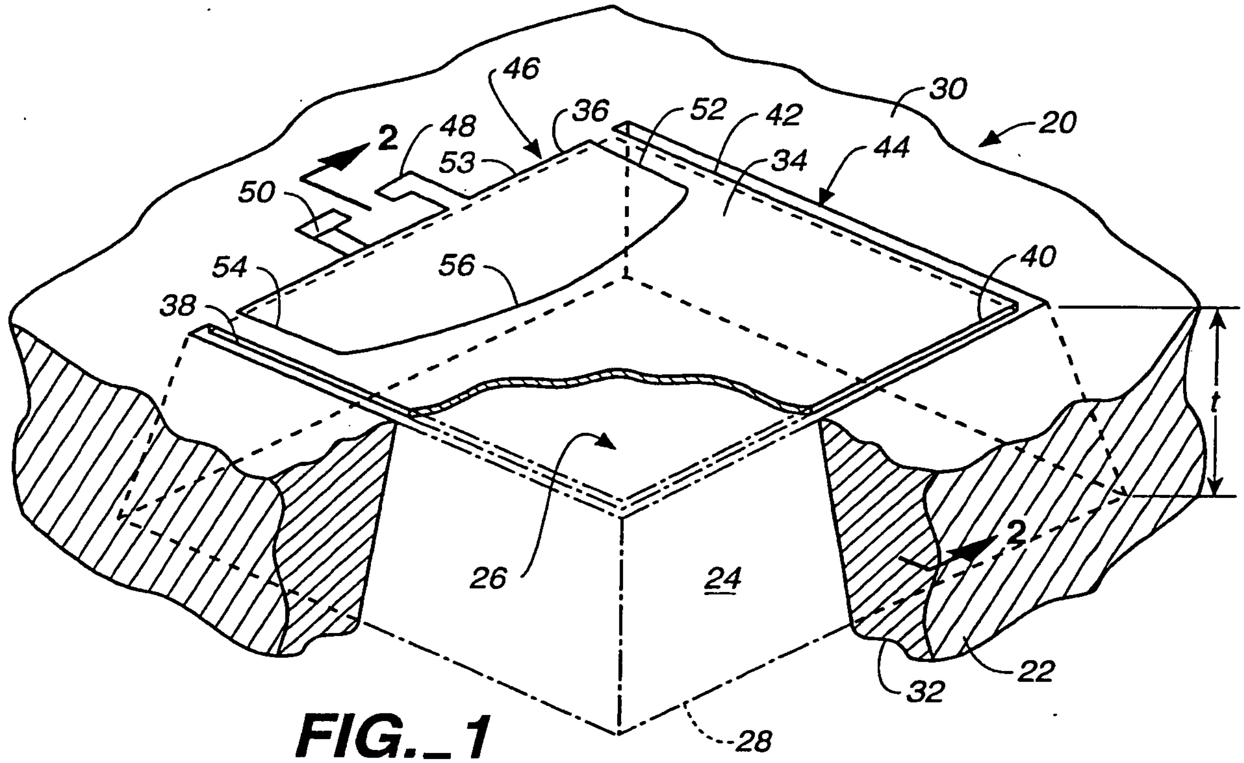

46
36
52
42
30
20
2
48
53
34
44
50
54
56
40
38
t
26
24
2
22
32
28

FIG._1

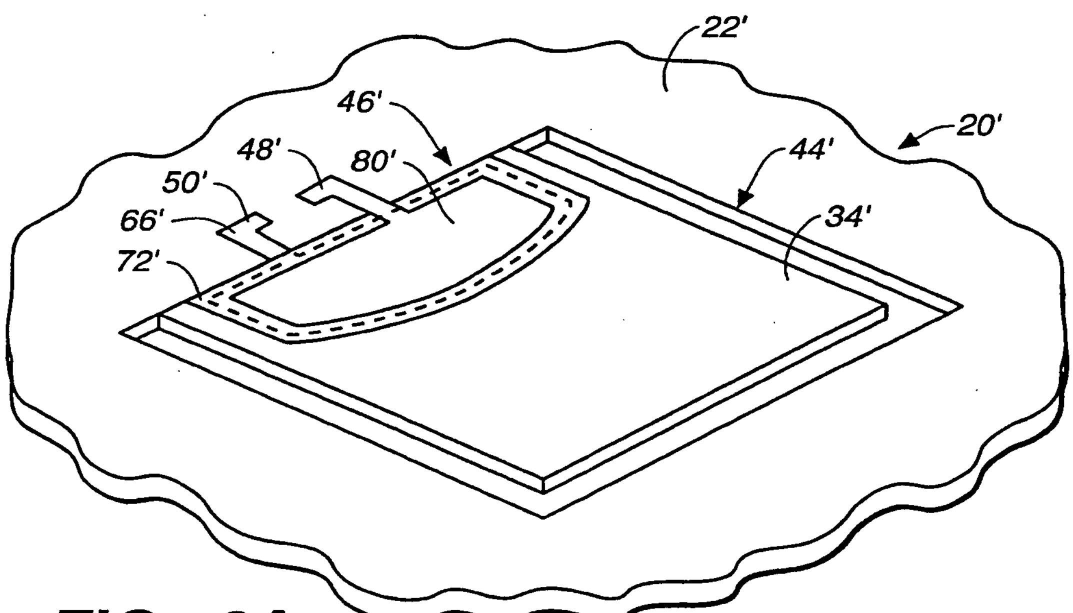

22'
46'
20'
48'
80'
44'
50'
66'
34'
72'

FIG._3A

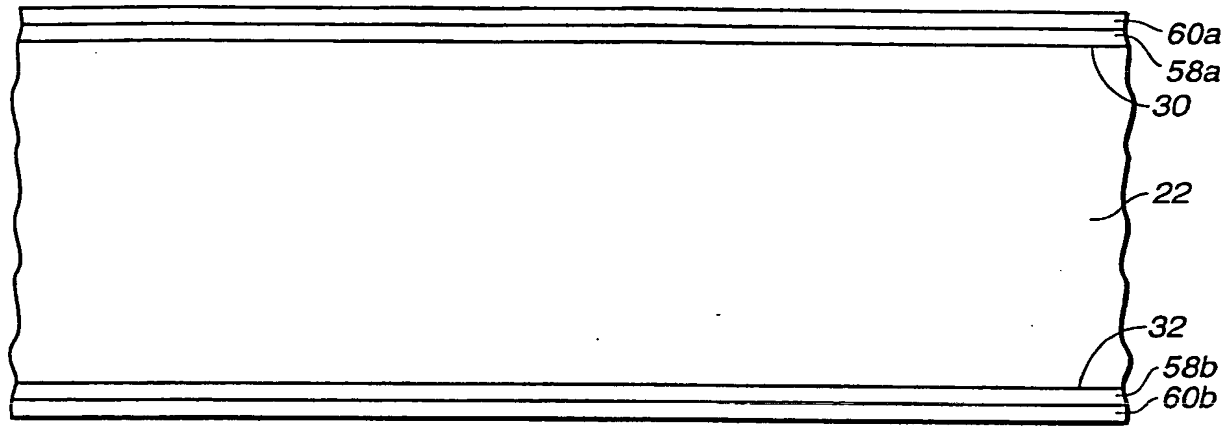


FIG._2A

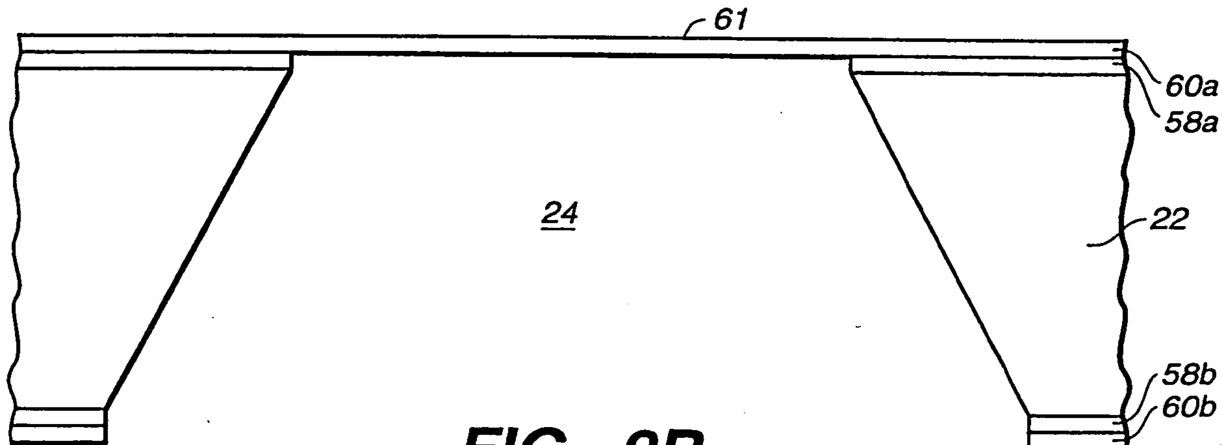


FIG._2B

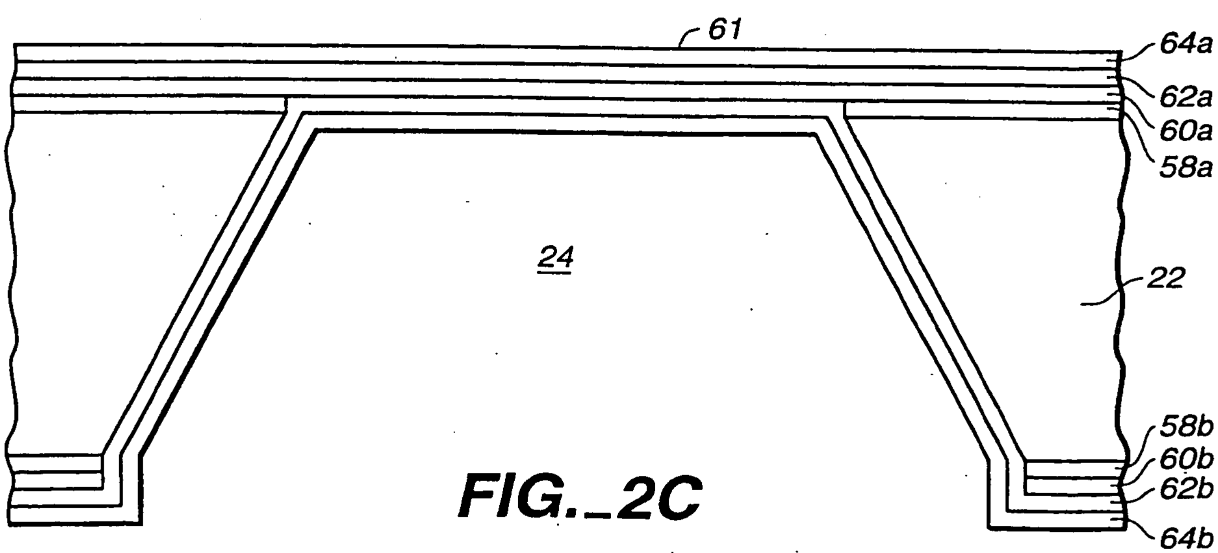
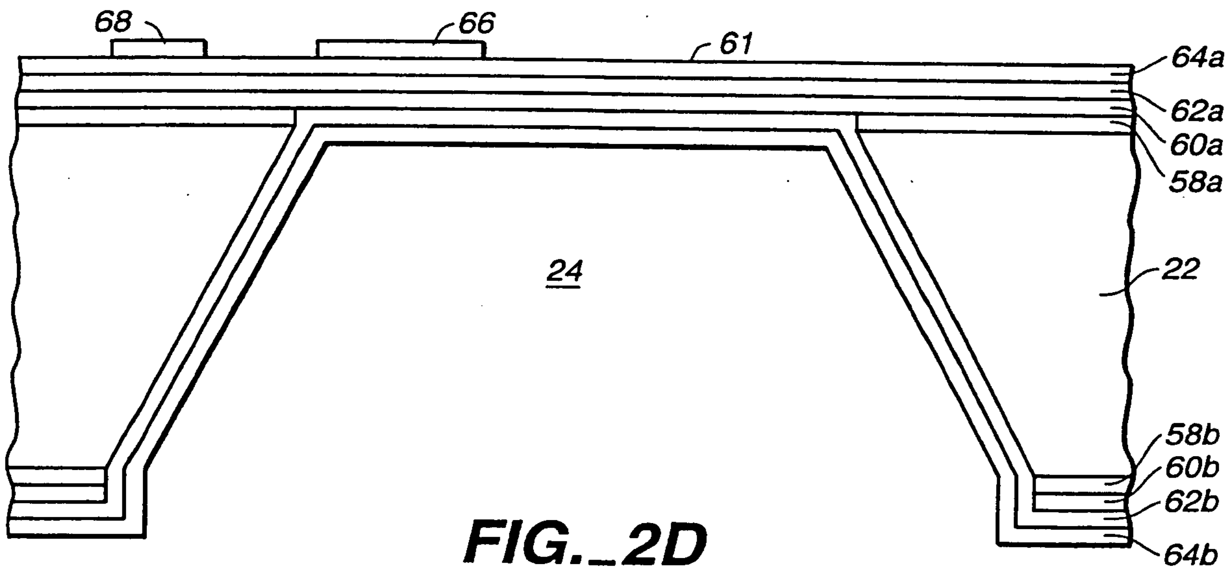


FIG._2C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66
61
64a
62a
60a
58a
24
22
58b
60b
62b
64b

FIG._2D

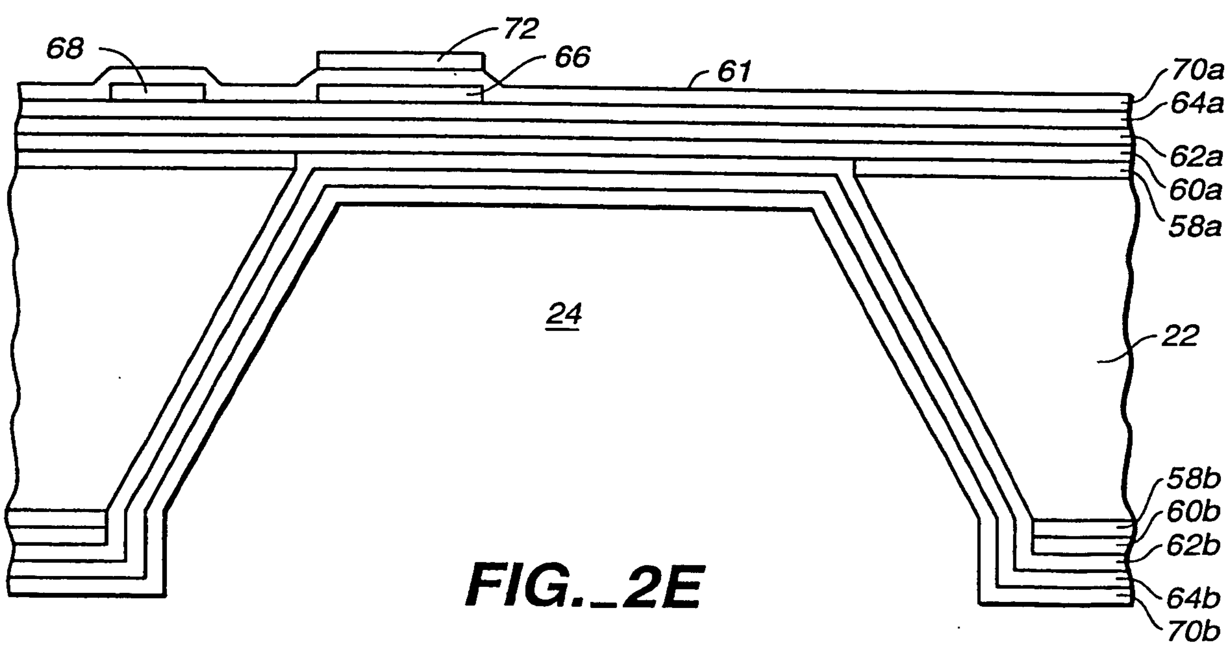

72
68
66
61
70a
64a
62a
60a
58a
24
22
58b
60b
62b
64b
70b

FIG._2E

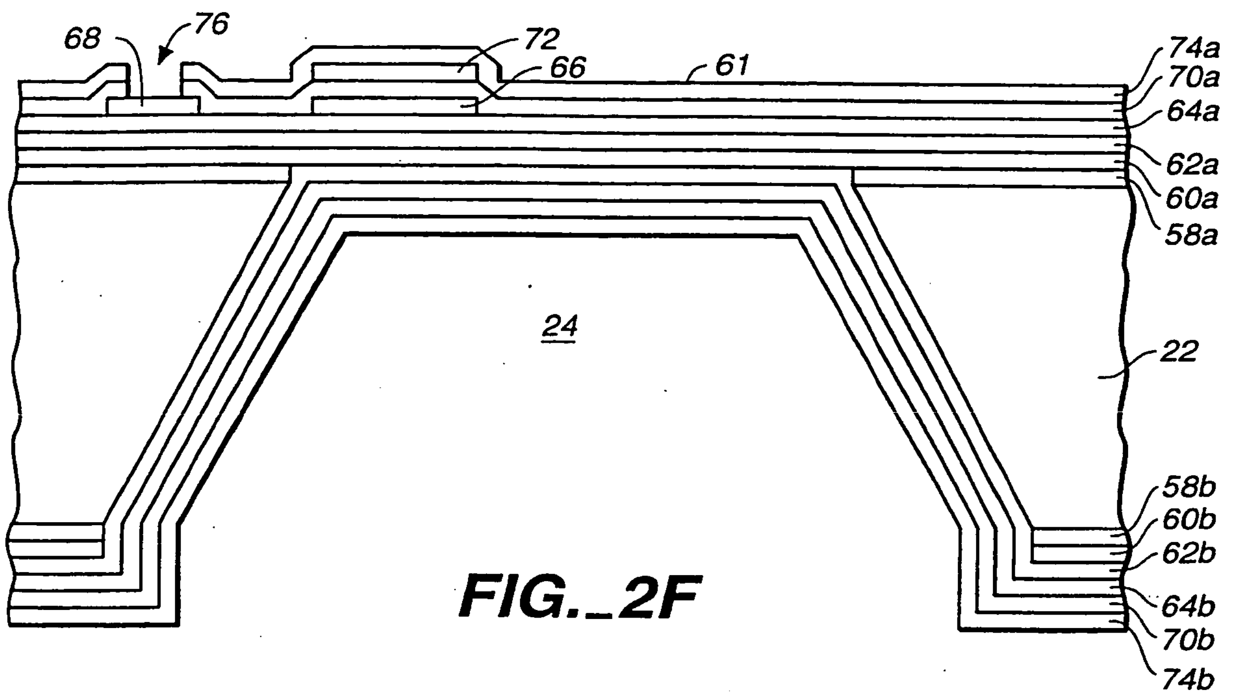

68
76
72
66
61
74a
70a
64a
62a
60a
58a
24
22
58b
60b
62b
64b
70b
74b

FIG._2F

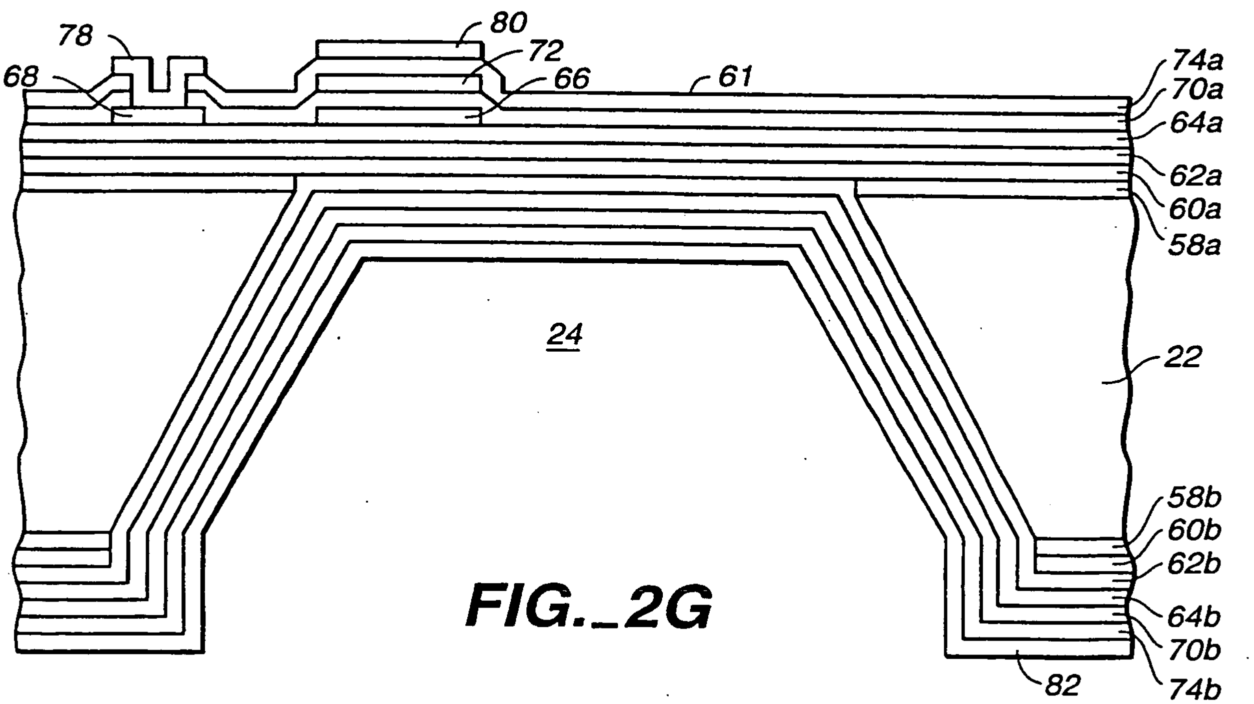

78
80
72
68
66
61
74a
70a
64a
62a
60a
58a
24
22
58b
60b
62b
64b
70b
74b
82

FIG._2G

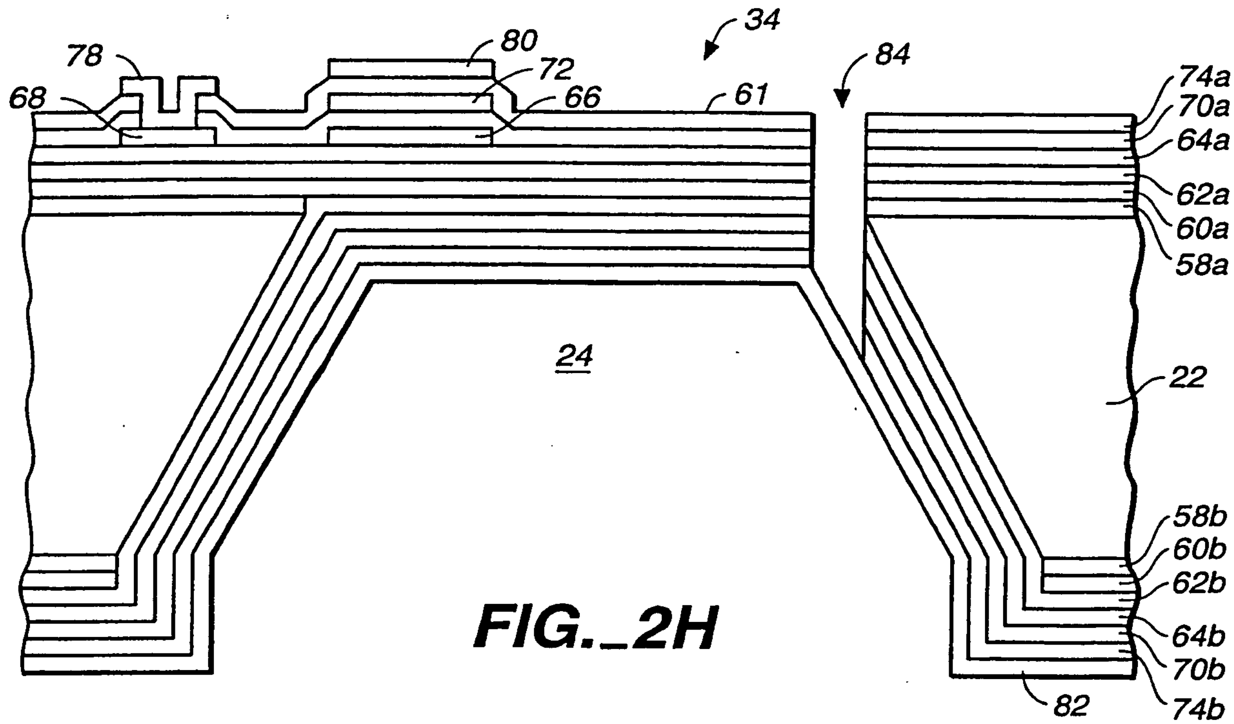

34
80
78
84
72
68
66
61
74a
70a
64a
62a
60a
58a
24
22
58b
60b
62b
64b
70b
82
74b

FIG._2H

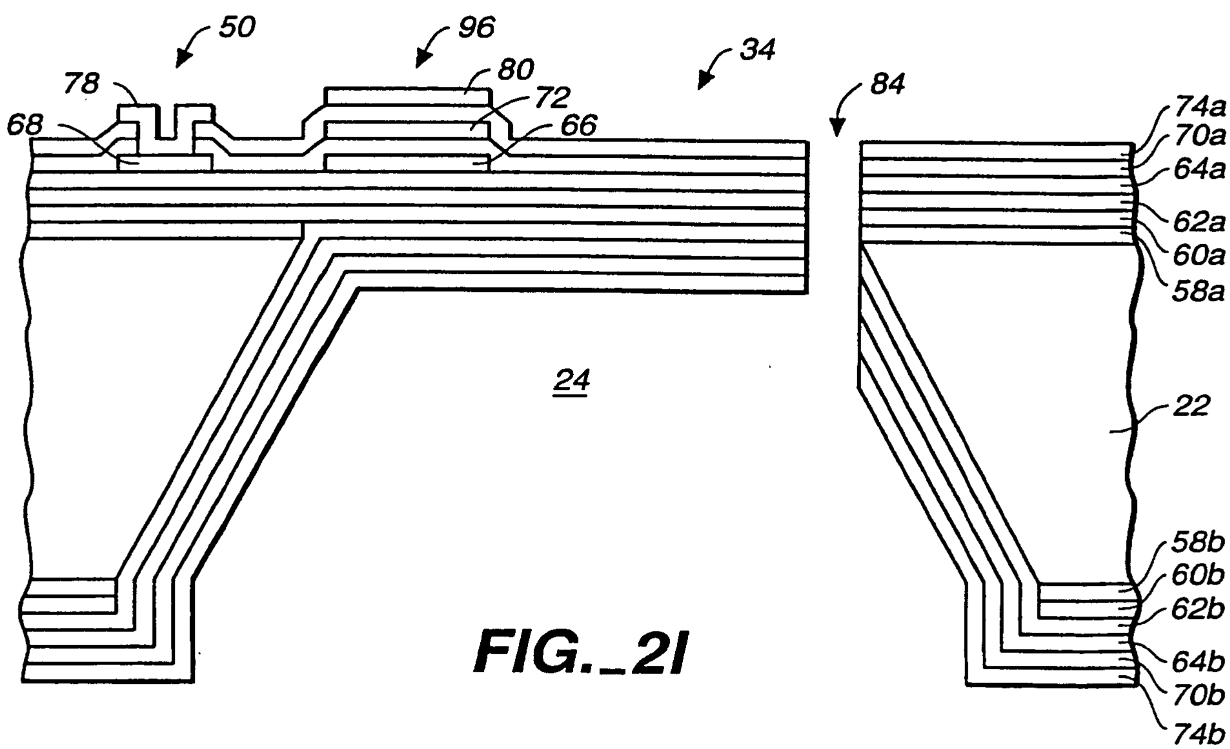

50
96
34
80
78
84
72
68
66
74a
70a
64a
62a
60a
58a
24
22
58b
60b
62b
64b
70b
74b

FIG._2I

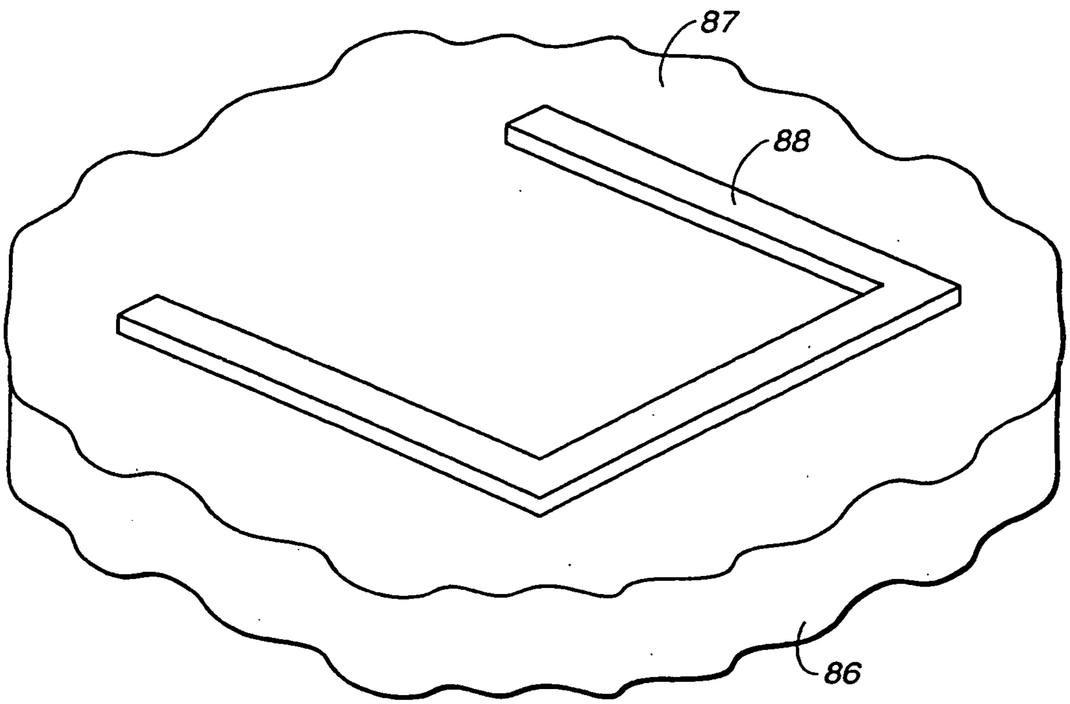


FIG._3B

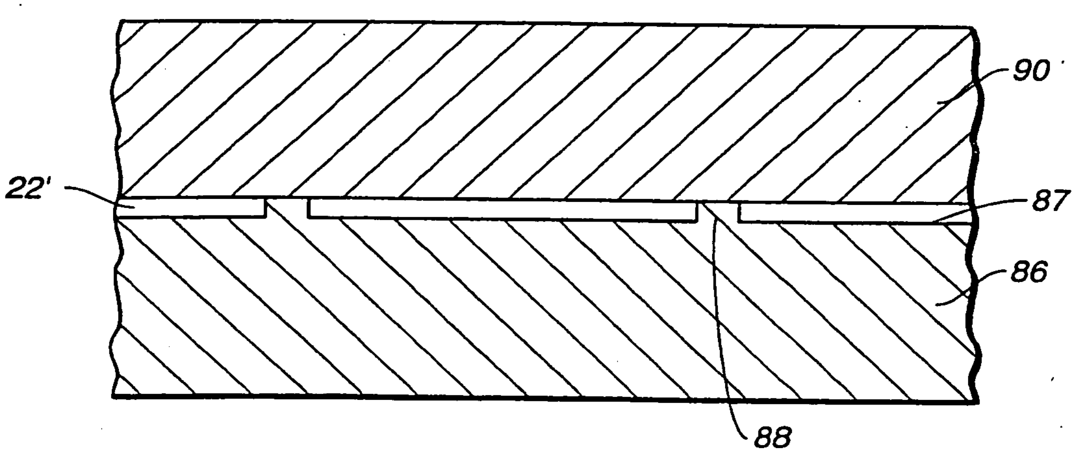


FIG._3C

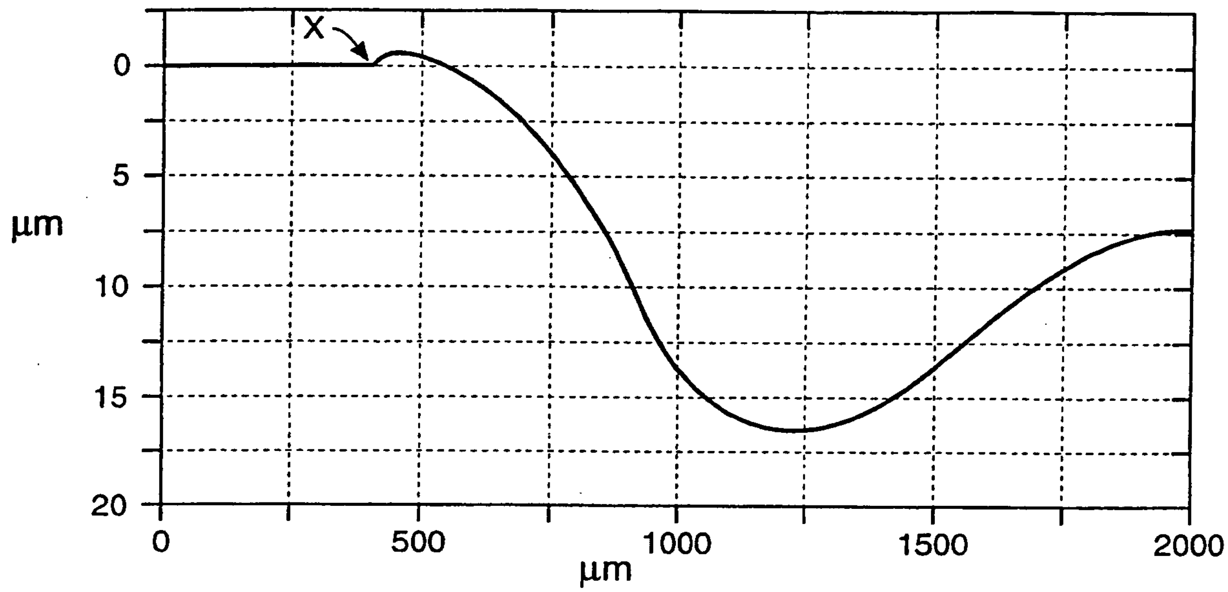


FIG._4

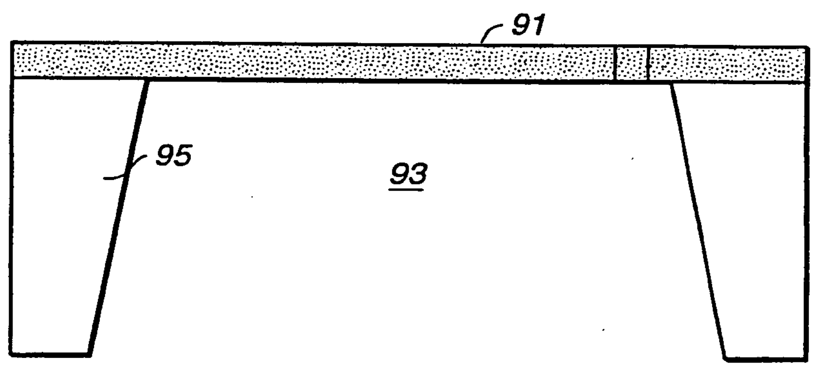


FIG._6A

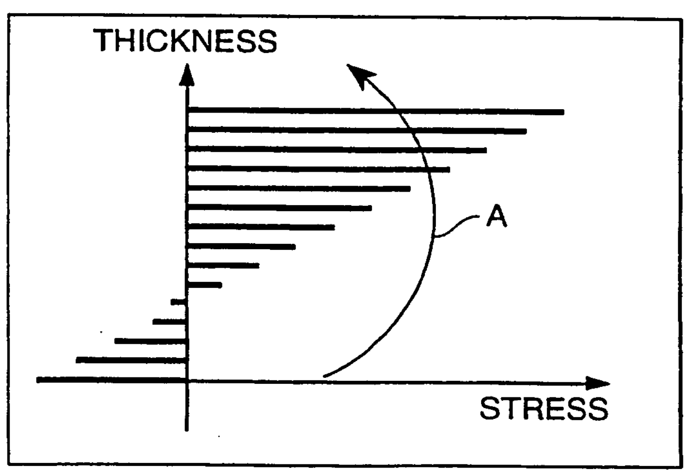


FIG._6B

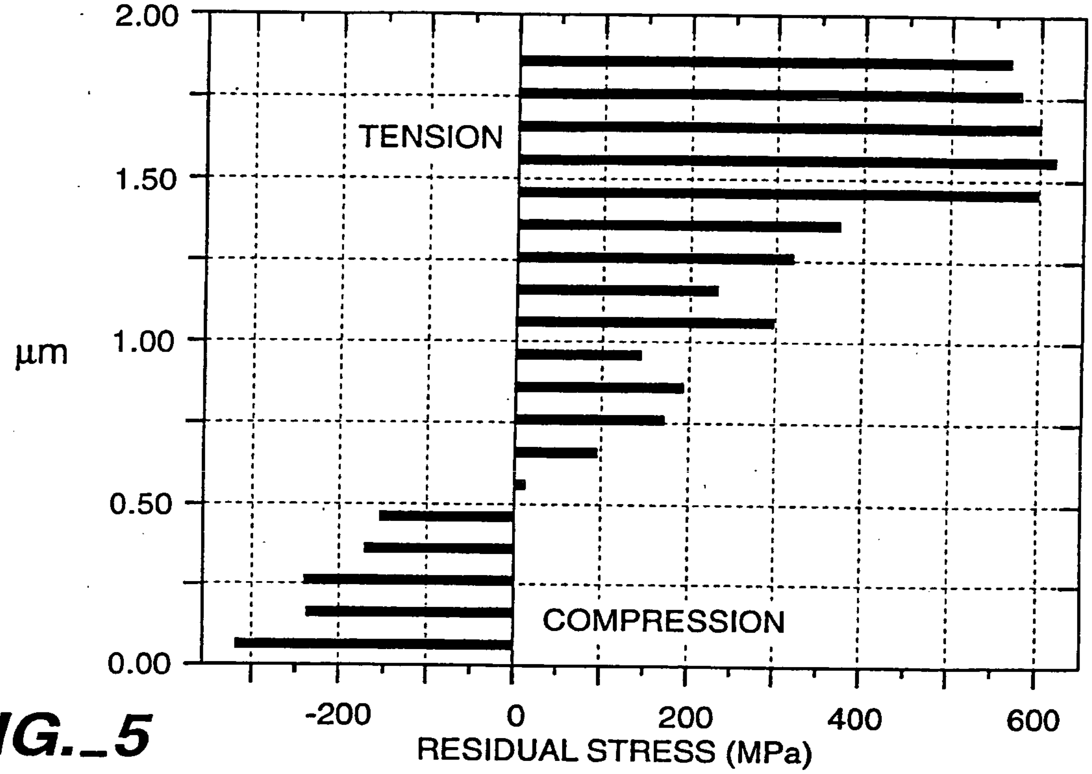


FIG._5

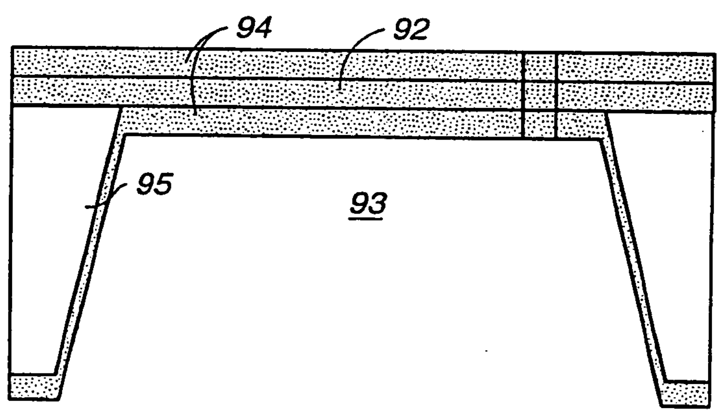


FIG._7A

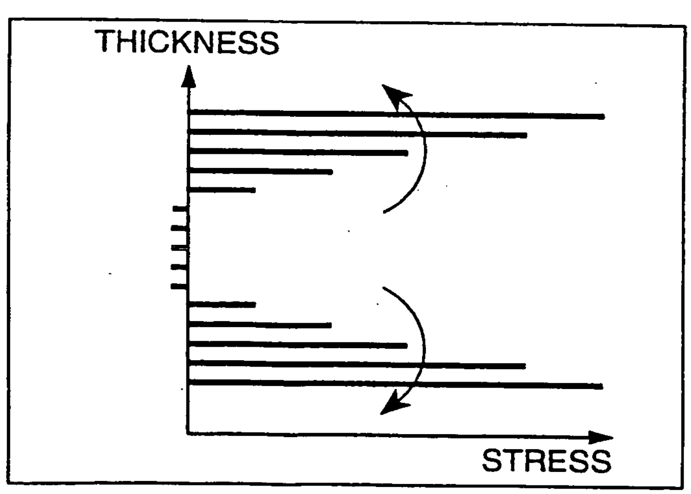


FIG._7B

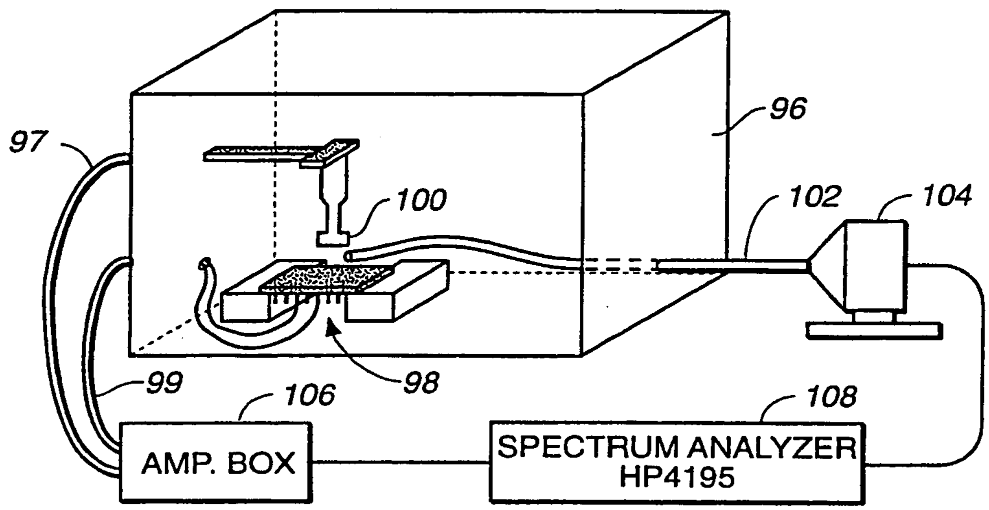

97
96
100
102
104
99
106
98
108
AMP. BOX
SPECTRUM ANALYZER
HP4195

FIG._8

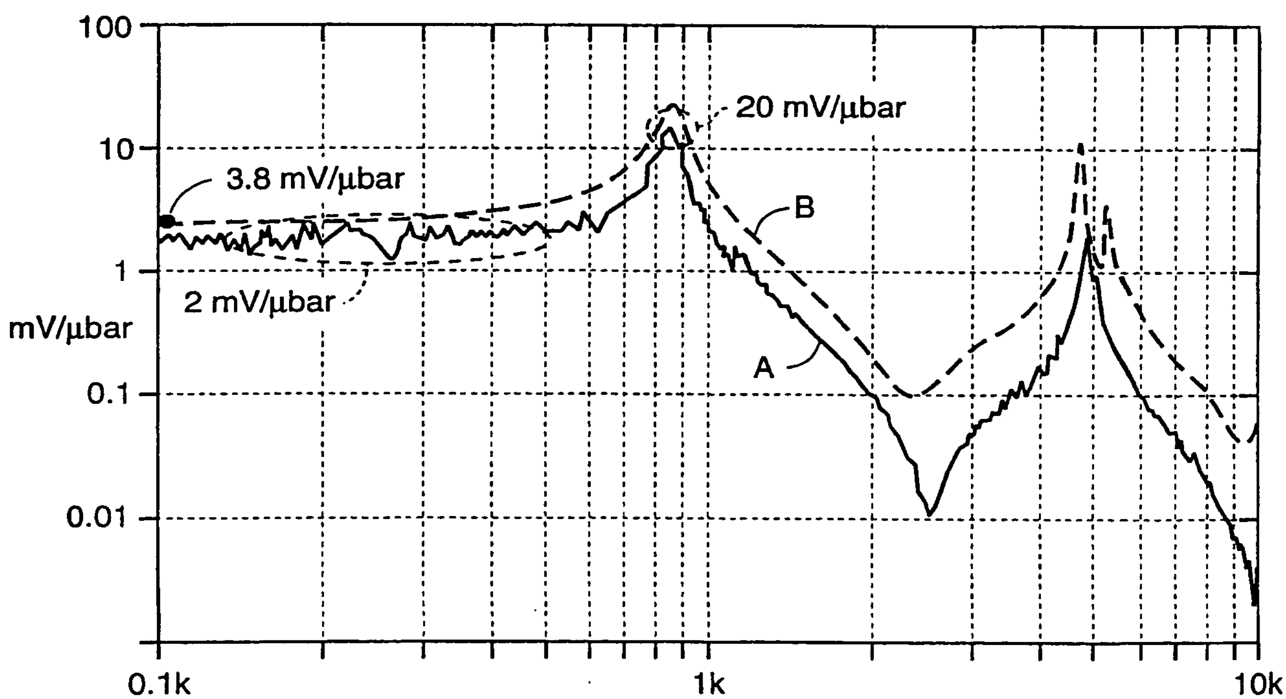

100
10
1
0.1
0.01
mV/µbar
3.8 mV/µbar
2 mV/µbar
20 mV/µbar
B
A
0.1k
1k
10k
FREQUENCY (kHz)

FIG._9

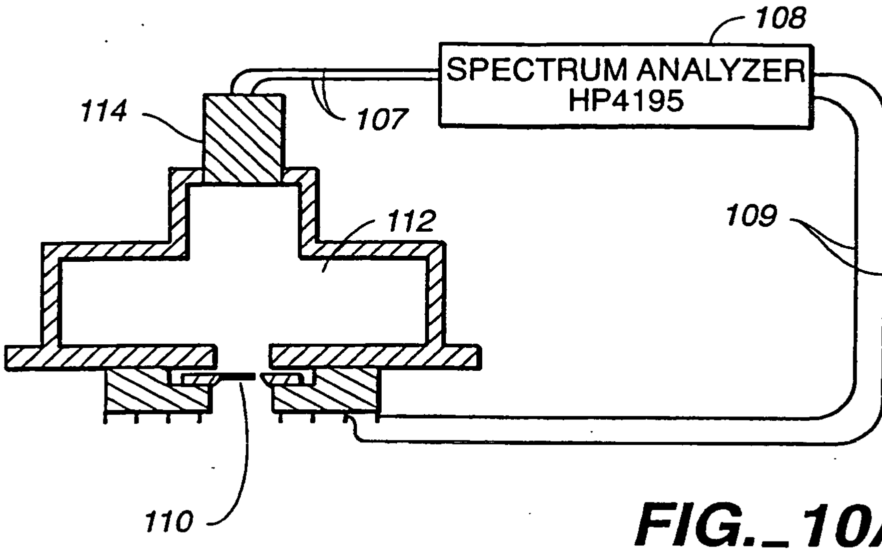
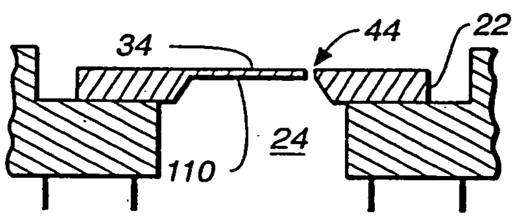


FIG._10A

FIG._10B



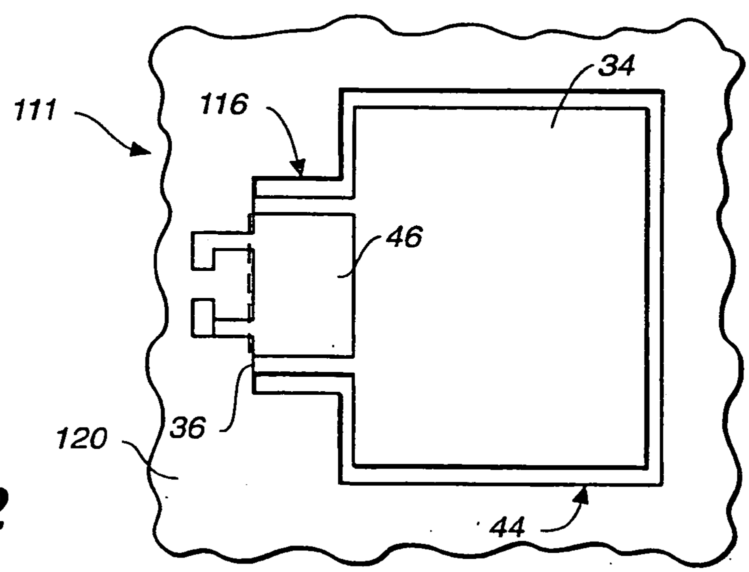


FIG._12

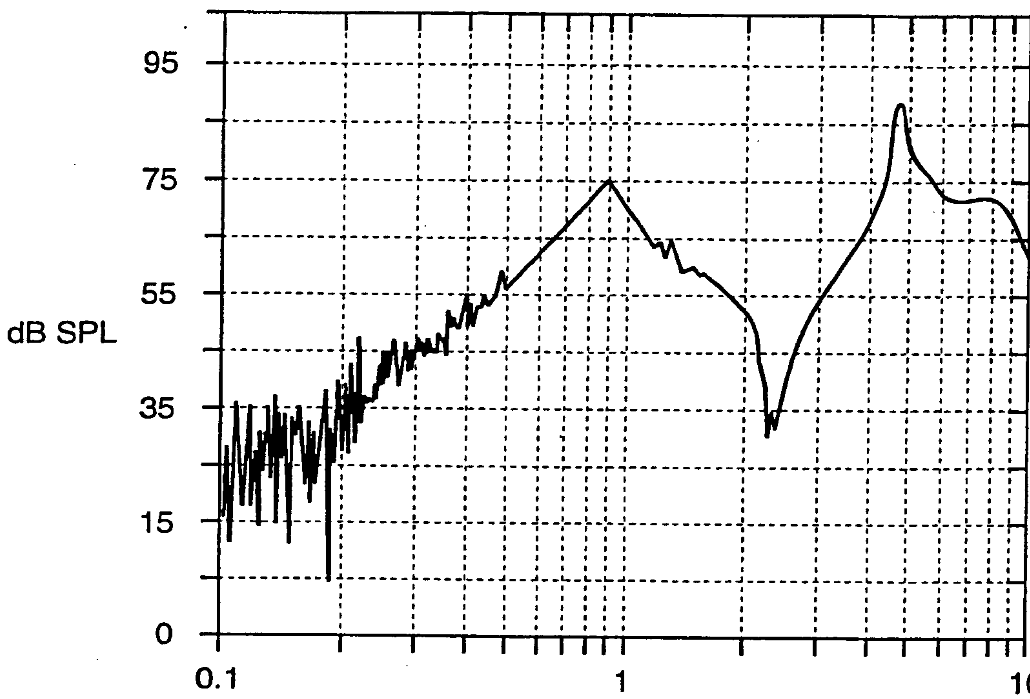


FIG._11A

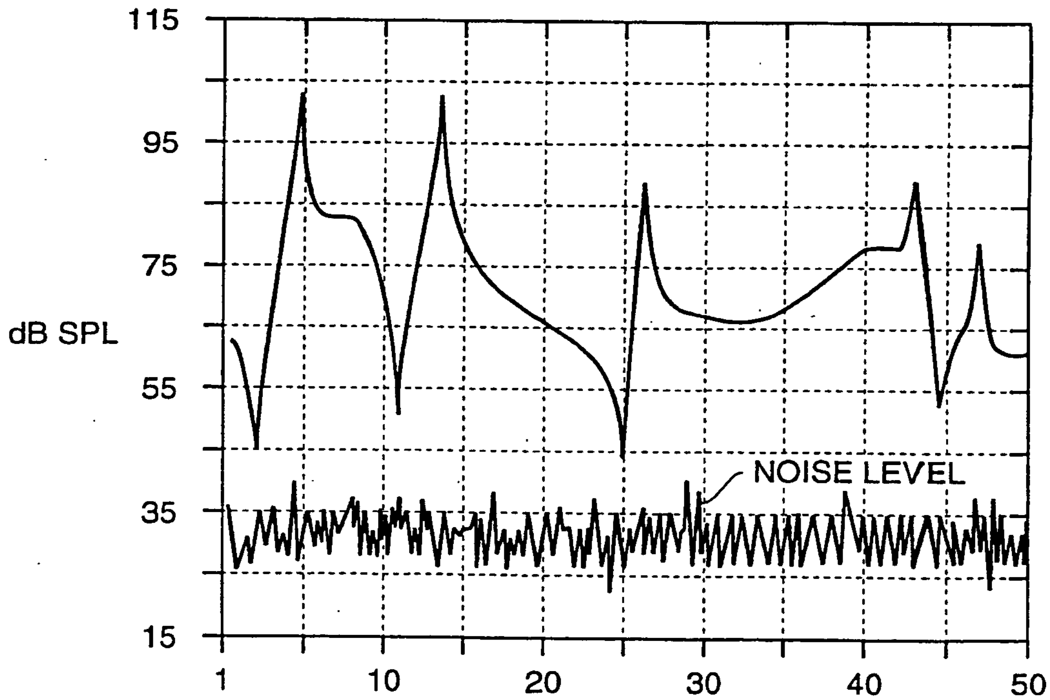


FIG._11B

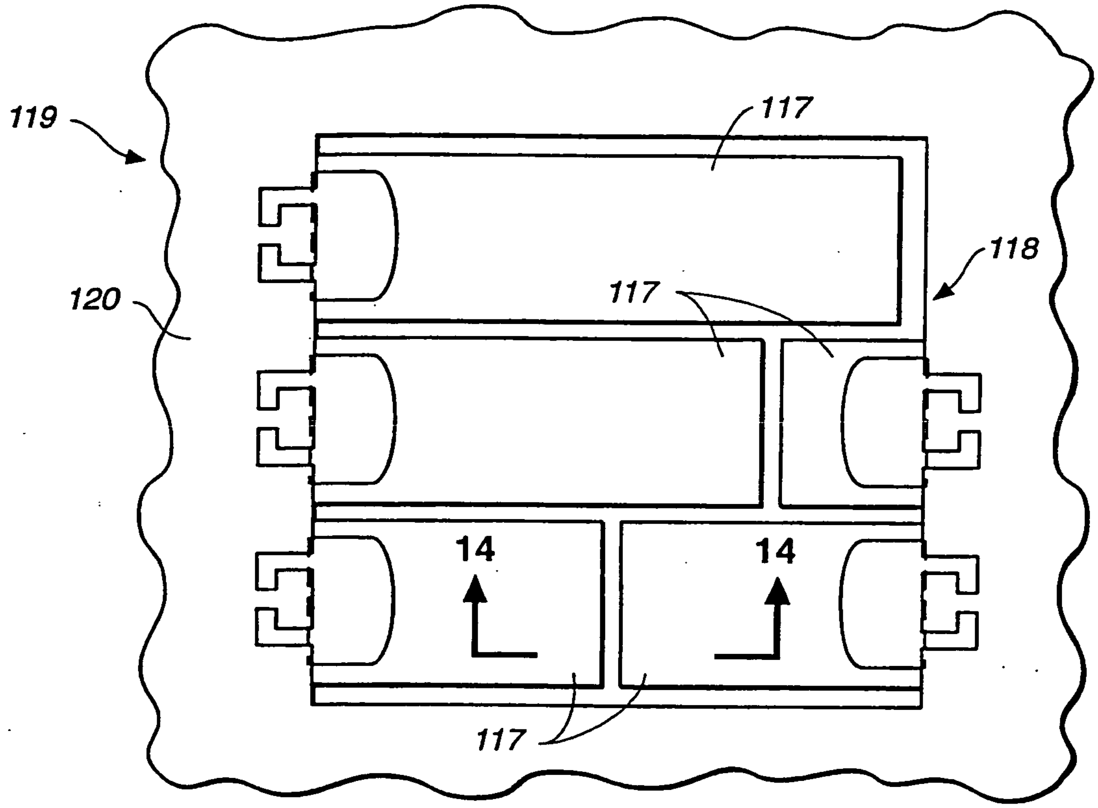


FIG._13

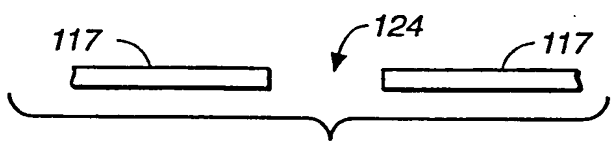


FIG._14A

FIG._14B

FIG._14C

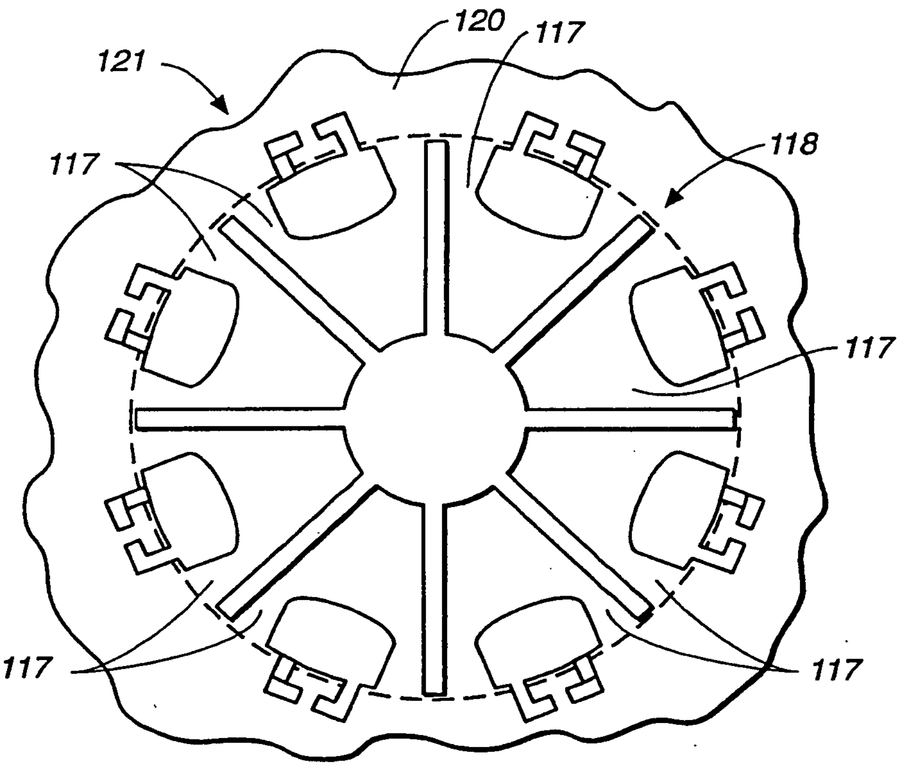


FIG._15

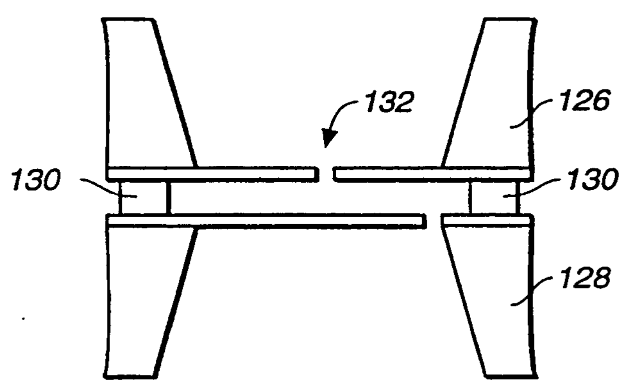


FIG._16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/05519

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01L 41/08, 21/318, 21/306
US CL :310/328,331,332,311; 29/25.35
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 310/328,331,332,311; 29/25.35

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS Text Search

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --,P Y	US,A, 5,339,289 (ERICKSON) 16 August 1994, figure 2; column 9, lines 30-32;col. 10, 1ines 10-14.	1,3,4,8 ------ 2,5-7,9-13
Y	US,A, 5,072,288 (MACDONALD ET AL) 10 December 1991 figure 1	2,9
Y	US,A, 5,049,775 (SMITS) 17 September 1991 figure 1; column 2, lines 45-50	5-7,10-13
X --,P Y	US,A, 5,138,216 (WOODRUFF ET AL) 11 August 1992, figure 16; figure 3; figure 14	1,4-8,11-14 16-19,21-24 ------ 38,39
A	US,A, 5,162,691 (MARIANI ET AL) 10 November 1992 see figs. 1 and 2	1,5,17,19, 38

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

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"E" earlier document published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

11 JULY 1995

Date of mailing of the international search report

31 JUL 1995

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Authorized officer
THOMAS DOUGHERTY
Telephone No. (703) 308-1628

Form PCT/ISA/210 (second sheet)(July 1992)*

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US95/05519

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A, 5,260,596 (DUNN ET AL) 09 November 1993 see fig. 1.	1,5,6,15,17
A,P	US,A, 5,366,587 (UEDA ET AL) 22 November 1994 see figs. 1A-1J	26-36
A,P	US,A, 5,396,066 (IKEDA ET AL) 07 March 1995 see figs. 1A, 6A, 7	1,14
A	US,A, 5,418,771 (KASANUKI ET AL) 23 May 1995 see fig. 1A, 2, 13, 14	1,5,6,14,16,17
A	US,A, 5,001,933 (BRAND) 26 March 1991 see fig. 5	1,5,6,14,16,17
A	JP,A, 4-186784 (HASEGAWA) 03 July 1992 see figs. 1a-1c, 2, 3	1,5,17,19, 21, 27,38,39